Received 11/30/04
MSHA/OSRV

SAFETY ANALYSIS OF TRAILING CABLES USED ON HIGH VOLTAGE CONTINUOUS MINERS

Prepared for

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September 2004

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EXECUTIVE SUMMARY

Joy Mining Machinery requested a safety study of cables used on 2400-V continuous miners compared with cables used on low and medium-voltage machines. As a result, analyses were performed to determine whether an increased shock hazard occurs with the 2400-V system, as compared with existing low and medium-voltage systems if *MSHA's Proposed Rule for High-Voltage Continuous Mining Machines* was implemented except for the special cable-handling requirements. Two major differences between the high-voltage proposed rule and existing low and medium-voltage regulations that are relevant to these analyses deal with ground-fault protection and include:

- The maximum ground-fault current of the 2400-V system must be limited to 0.5 A, while the low and medium-voltage systems typically use a limit of 15 A.

  and

- The maximum ground-fault pickup of the 2400-V system must be set at 0.125 A with a maximum time delay of 0.05 s; whereas, low and medium-voltage systems require an instantaneous pickup set at, or below, 40% of the maximum ground-fault current (6 A for 15-A systems).

The study was approached by investigating answers to the following two questions:

- Is a trailing cable on a 2400-V system more likely to be damaged and cause a shock hazard as compared with cables used on existing low and medium-voltage systems?

  and

- If a direct-contact shock does occur on a 2400-V system with the more stringent ground-fault requirements, is it more dangerous than one from an existing low or medium-voltage system?

The first question was addressed by analyzing the cable construction used at the various voltage levels, and three representative shock-hazard scenarios were selected to evaluate the effectiveness of each cable type. The second question was addressed by analyzing the severity of a direct-contact shock at the different voltage levels for various body resistances. The results of both analyses revealed that the 2400-V trailing cable, in conjunction with the strict ground-fault protection requirements and enhanced cable construction, was actually as safe, or safer, than the trailing cables used on low and medium-voltage continuous miners.

BACKGROUND AND INTRODUCTION

The continual search for improved productivity in the coal mining industry has resulted in a consistent trend towards larger coal-extraction equipment. The power requirements of these high-capacity machines have appreciably increased in recent years. In fact, these power requirements, in many instances, have reached the point where the practice of using 1000 V as the utilization voltage has become inadequate for the following reasons (Novak and Kohler, 1998, Novak and Martin, 1996, Morley, et al., 1990):

- excessive three-phase and line-to-line fault currents,
- massive cable sizes,
- reduced motor torque from excessive voltage drop, and
- difficulty in maintaining the maximum instantaneous trip settings allowed by the Mine Safety and Health Administration (MSHA).

The limitations of the 1000-V utilization system were first realized with longwall mining in the mid 1980's. At that time, however, the use of high voltage (greater than 1000 V) to power face equipment was not permitted by 30 CFR § 75.1002, which states:

> *Trolley wires and trolley feeder wires, high-voltage cables and transformers shall not be located inby the last open crosscut and shall be kept at least 150 ft from pillar workings.*

Thus, in order to exploit the benefits of high-voltage utilization, a mine operator was required to submit a 101-c Petition for Modification and demonstrate to MSHA that the proposed alternative method will at all times guarantee no less than the same measure of protection afforded by the existing standard.

Prior to 1986, all longwalls in the United States operated at utilization voltages less than 1000 V. The first MSHA experimental permit (initially used instead of a 101-c Petition for Modification) for high-voltage on-board switching was granted for a 2400-V longwall system in 1985. Within three years, ten other 2400-V longwall systems were in operation (Boring and Porter, 1988). By 2002, all longwalls in the United States were utilizing high voltage (2400 V or 4160 V) (Novak, et. al, 2004), and in March of 2002, MSHA eliminated the requirement to file a Petition by promulgating an update of 30 CFR Parts 18 and 75 which now includes provisions for operating high-voltage longwall equipment.

In the mid 1990's the mining industry again reached the operational boundaries of the 1000-V utilization system; but this time, continuous-mining operations were constrained by power limitations. High-voltage longwalls had now demonstrated safe, reliable, and highly productive operation for a decade. As a result, the process of submitting Petitions for Modification for 2400-V continuous miners commenced in 1997. MSHA granted 38 Petitions by July, 2004, at which time it submitted its proposed rule for high-voltage mining machines.

Although the two mining methods differ appreciably, the proposed regulations for high-voltage continuous-mining machines have some similarities to the promulgated high-voltage longwall regulations, such as reduced limits on ground-fault currents and lower pickup settings for ground-fault relays. In both mining systems, special precautions are required with respect to cable handling, as compared with low and medium-voltage trailing cables. These requirements are not particularly cumbersome for longwall mining since cables are typically supported by a monorail system up to the working face and are routed to the shearer and various motors through steel troughs on the stage loader and armored face conveyor. Energized cables rarely require manual handling except when a cable needs to be trained. This minimal cable handling, however, is not the case with a continuous miner in a room-and-pillar operation. A monorail system is impractical, and the continuous miner's trailing cable must frequently be handled manually, particularly with each place change. The rigorous cable-handling requirements for high-voltage continuous miners have lessened the potential productivity gains to a point where mine operators are asking why 2400-V trailing cables cannot be treated the same as low and medium-voltage trailing cables. The obvious reason for the stringent requirements is to provide additional shock protection for workers because of the increased voltage. However, with the other proposed safety requirements in place, the following question arises, "Is there truly an increased shock hazard associated with the 2400-V system, as compared with existing low and medium-voltage systems?" The remaining portion of this report addresses this question. Although the proposed regulations deal with high voltage, which include utilization voltages up to 4160 V, the discussions in this report are only directed toward the 2400-V system, since this is the voltage presently being used for high-voltage applications of continuous miners.

ELECTRIC SHOCK HAZARD

According to the discussion in the proposed rule, the rationale for strict cable-handling requirements hinges on the possibility that "A damaged cable may expose energized conductors, and thereby present a shock hazard to miners." Thus, two questions need to be answered:

1. Is a trailing cable on a 2400-V system more likely to be damaged and cause a shock hazard as compared with cables used on existing low and medium-voltage systems?

   and

2. If a direct-contact shock does occur on a 2400-V system, is it more dangerous than one from an existing low or medium-voltage system?

Each question is addressed in the following two major sections – "Cable Safety Analysis" and "Shock Analysis," respectively.

CABLE SAFETY ANALYSIS

The construction of continuous-miner trialing cables used at low, medium, and high voltages will be analyzed to determine the effectiveness of each in protecting workers from a shock hazard. A trailing cable basically consists of power conductors, grounding conductors, a ground-check conductor, shielding, insulation, binding, fillers, and a jacket. However, low-voltage cables (< 660 V) are not required to be shielded. Federal regulations permit the use of SHC shielding on medium-voltage cables (661 V – 1000 V), where a single conductive shield encircles all conductors; but SHD shielding, which encircles the insulation of each power conductor separately, is typically used. High-voltage cables are required to have SHD shielding. In addition to electrical-insulation considerations, the design of trailing cables must accommodate physical stresses that are encountered in the harsh mining environment, some of which include tension, flexing, abrasion, and crushing. Thus, trialing-cable construction must be very robust to endure severe operating conditions. Typical cable construction for each of the three voltage levels will be discussed below.

Low-Voltage Cable. A typical trailing cable used at low voltage (480 V or 600 V) is 4/0-AWG 2-kV Type G-GC, which is shown in Figure 1. The 4/0 power conductors (tinned rope bunched compressed copper) are arranged is a symmetrical fashion. A white mylar tape encircles each power conductor and acts as a *separator* between the conductor and its insulation. The insulation around each power conductor consists of a minimum average of 80 mils of ethylene-propylene rubber, which is colored red, white, or black for phase identification. Rubber filler is used to fill the void at the center interstice. Two #2-AWG grounding conductors, covered with green mylar tape, are located at two interstices of the insulated phase conductors. A #8-AWG ground-check conductor, insulated with 45 mils of polypropylene, is located at the third interstice. (It should be noted that G+GC cables, where the ground-check conductor is located at the center interstice, can also be used at all voltage levels.) An inner jacket of approximately 60 mils of HD black chlorinated polyethylene and an outer jacket of approximately 145 mils of EHD black chlorinated polyethylene encircle the entire cable assembly. Two reverse/open wraps of polypropylene filament, located between the inner and outer jackets, are used for reinforcement.

Medium-Voltage Cable. Figure 2 shows a typical arrangement for a 2/0-AWG 2-kV Type G-GC trailing cable used for medium voltage (1040 V). The increased voltage allows for smaller phase (2/0 AWG) and ground (#3 AWG) conductor sizes for a given power requirement. The construction is quite similar to that of the low-voltage cable with one major exception – the braided shield. Like the low-voltage cable, each phase conductor is covered with a layer of mylar tape followed by 80 mils of ethylene-propylene rubber. The insulation is wrapped with rubber-backed-fabric tape, helically applied and lapped. However, unlike the low-voltage application, a copper/nylon braided shield encircles the fabric tape. The braided shield provides a 60% minimum of copper coverage. The shielding for all three phases intimately contacts the grounding conductors for the entire length of cable. The size and location of the ground-check conductor are the same as those for the low-voltage cable.

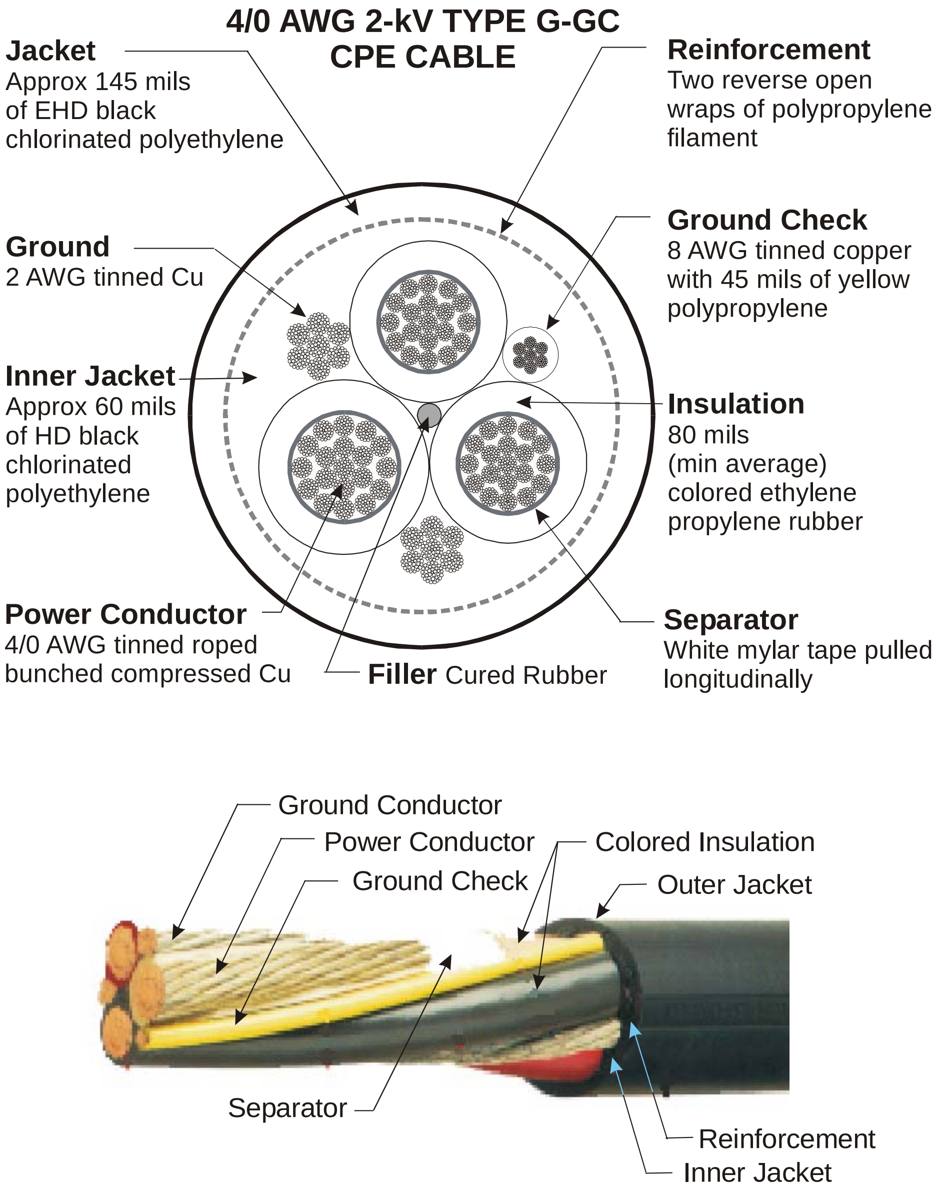

Figure 1. Typical trailing cable for a low-voltage (440 V or 550 V) continuous miner.

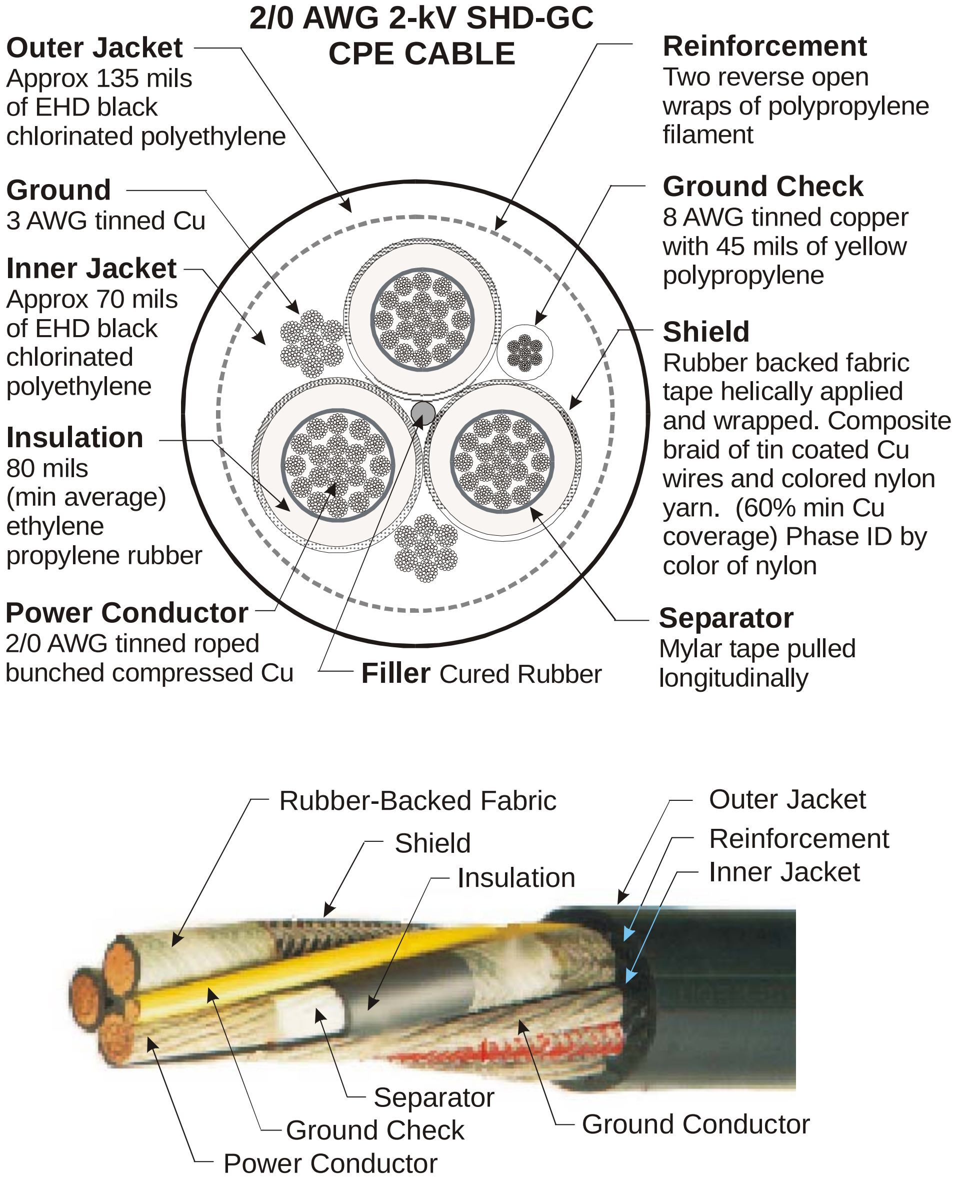

Figure 2. Typical trailing cable for a medium-voltage (950 V) continuous miner.

The inner and outer jackets are both constructed of EHD black chlorinated polyethylene with thicknesses of 70 mils and 135 mils, respectively. As with the low-voltage cable, polypropylene filament is used for reinforcement between the two jackets.

High-Voltage Cable. The 1/0-AWG 5-kV SHD-GC INT ORANGE cable, which is shown in Figure 3, is a typical continuous-miner trailing cable that is required by the proposed regulations. Again, because of the higher voltage, the phase (1/0 AWG) and grounding (#4 AWG) conductors are smaller in size, compared with the lower-voltage levels. The size and location of the ground-check conductor, and the general arrangement of the cable, are similar to those of the medium-voltage cable. However, there are several major differences with the construction of the two cables. These differences include:

- Instead of the mylar-tape separator, the high-voltage cable has a 15-mil strand shield that is made of extruded semi-conducting compound and encircles each phase conductor. The purpose of this shield is to eliminate peaks in the strands and reduce electric stress on the insulation, while adding a layer of mechanical protection.

- The ethylene-propylene insulation around the strand shield on each phase is increased from 80 mils to 110 mils.

- A semi-conducting butyl/nylon tape is helically applied, and lapped, around the insulation on each phase, instead of the fabric tape used on the medium-voltage cable. This semi-conducting tape, in conjunction with the braided nylon/copper shield, virtually provides 100% coverage of the insulation.

- The inner and outer EHD chlorinated polyethylene jackets have distinct colors – green and orange, respectively. This feature enhances a worker’s ability to visually identify a damaged outer jacket.

- The combined thickness of the inner and outer jackets is 220 mils for the high-voltage cable, compare with 205 mils for the medium-voltage cable.

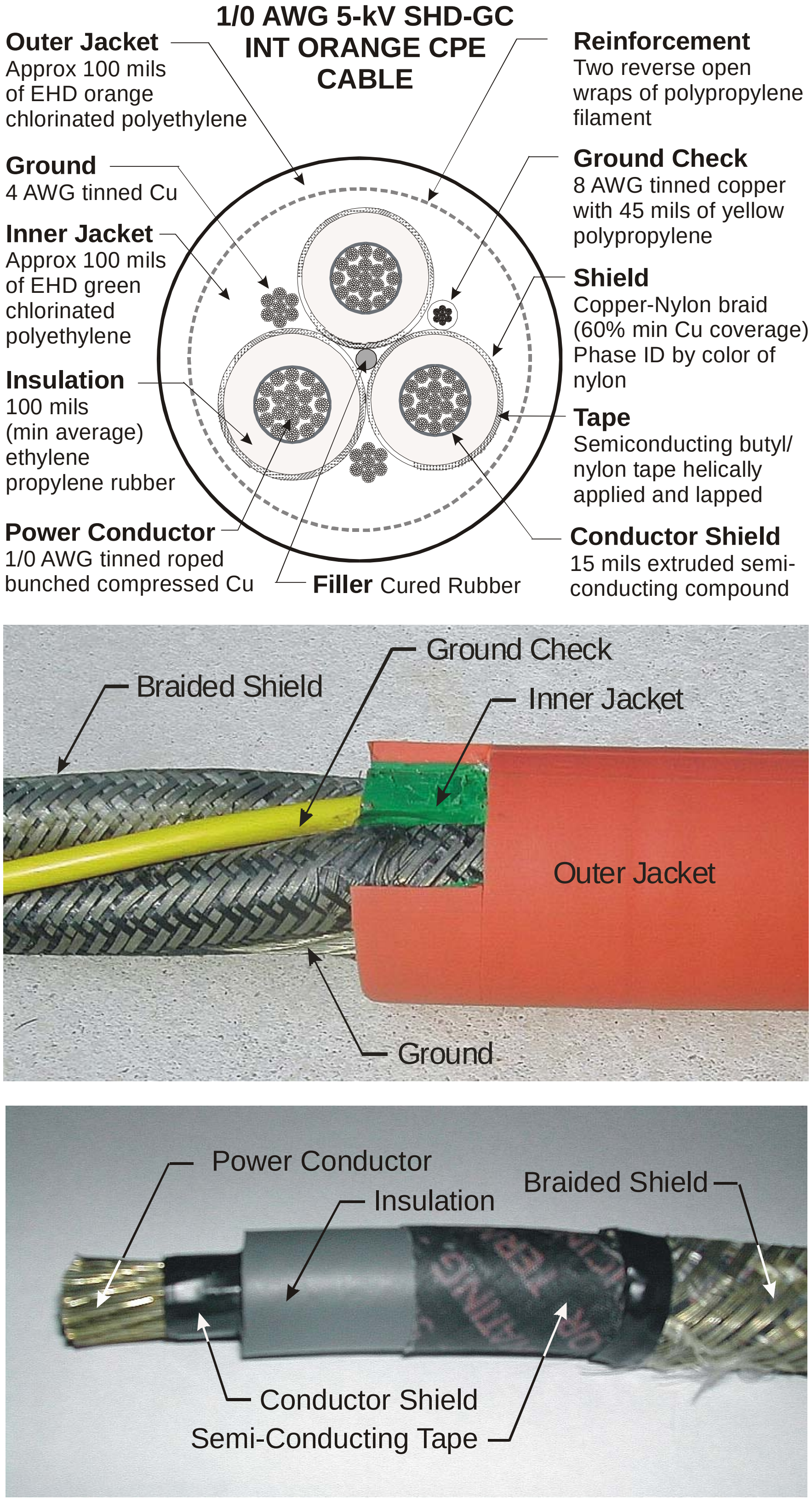

Figure 3. Typical trailing cable for a 2300-V continuous miner.

Circuit Model. Figure 4 is a generic model of a continuous-miner circuit for performing quantitative safety analyses at any system voltage. The model consists of the secondary winding of the three-phase power-center transformer and its associated impedance Z_t, along with the neutral grounding resistor R_{NG}, and the continuous-miner trialing-cable impedance Z_L. The neutral grounding resistor is connected between the neutral point of the *wye*-connected-transformer secondary and ground. The cable is modeled as a series-connected impedance Z_L (resistance and inductive reactance) in each phase and a shunt capacitive reactance X_C between each line conductor and ground. The shunt capacitive reactance is due to the inherent system capacitance between the phase conductors and ground. The resistor R_F is used to model the fault resistance for a line-to-ground fault.

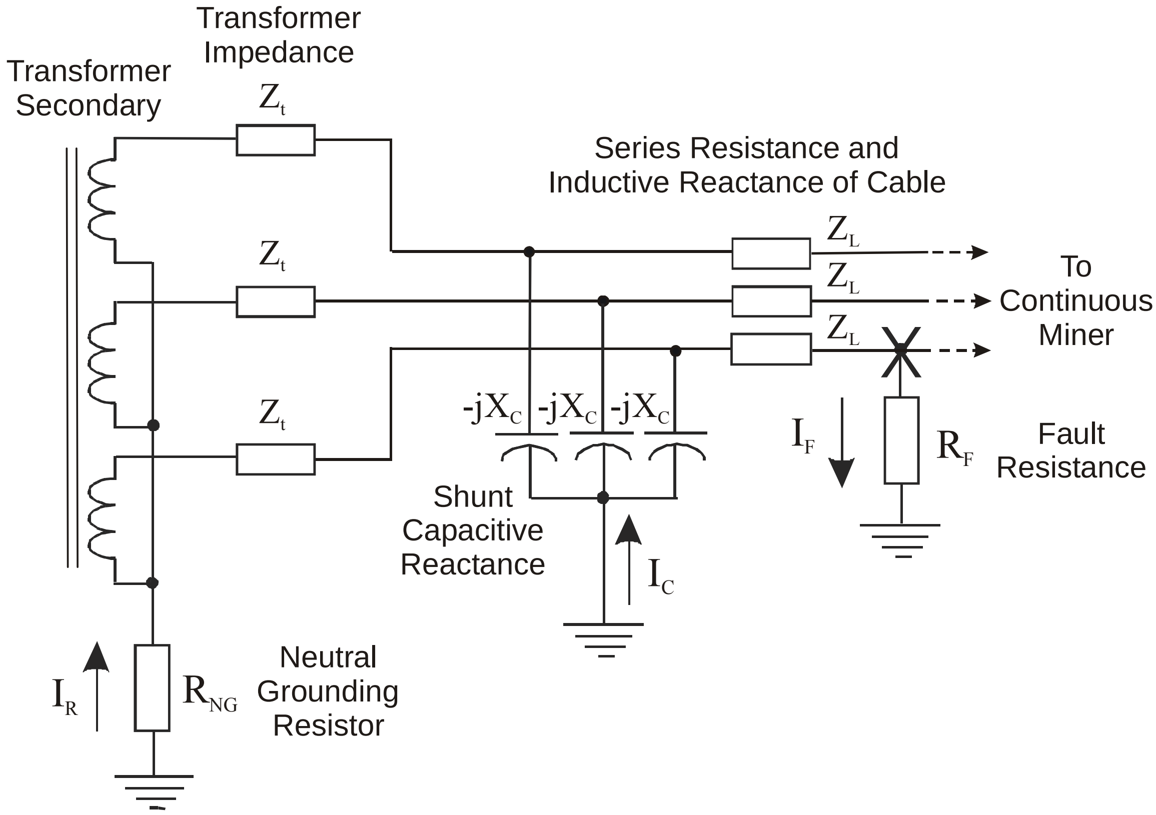

Figure 4. Three-phase generic circuit for modeling electrical hazards.

The three-phase circuit of Figure 4 can be reduced to the single-phase equivalent circuit of Figure 5. The transformer impedance Z_t and the line impedance of the cable Z_L are neglected since their values are negligible compared with that of the neutral grounding resistor. The values for the neutral grounding resistor and the reactance due to system capacitance are determined in the following sections.

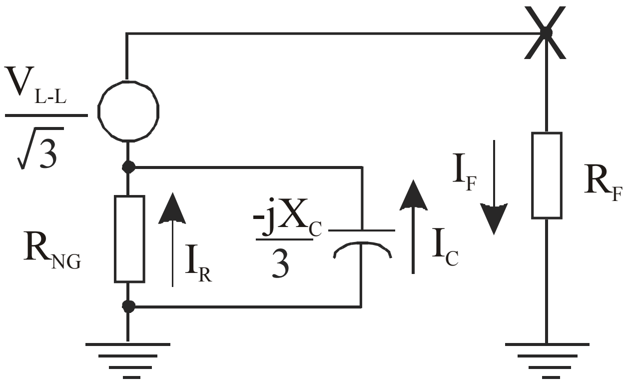

Figure 5. Simplified single-phase equivalent circuit of Figure 4 used for high-voltage analyses.

Neutral Grounding Resistor. The neutral grounding resistor R_{NG} is connected between the neutral point of the transformer and ground, to limit the maximum ground-fault current. Thus, the ohmic value of the neutral grounding resistor is based on the maximum ground-fault-current limit required by federal regulations. With high voltage, the actual ground-fault current is the phasor sum of the current returning to the transformer through the grounding resistor R_{NG} and the reactance due to system capacitance $X_C/3$. With low and medium-voltage systems, which have relatively small values for their neutral grounding resistors, the effect of system capacitance is insignificant and can be neglected. This is particularly true at low voltages, since shielded cables are not required. As a result, the following formula is traditionally used to determine the value of the neutral grounding resistor:

$$R_{NG} = \frac{\frac{V_{L-L}}{\sqrt{3}}}{I_{gf_{(\max)}}} \tag{1}$$

Equation 1 assumes a value of zero for the fault resistance R_F, which results in the maximum ground-fault current (bolted fault). For low and medium voltages, federal regulations require the maximum ground-fault current be limited to 25 A. However, throughout the years, common practice has been standardized to using 15 A. Therefore, the ohmic values of the neutral grounding resistors at low and medium voltages are calculated as follows:

480-V System: $$R_{NG} = \frac{\frac{480}{\sqrt{3}}}{15} = 18.5\ \Omega, \tag{2}$$

600-V System: $$R_{NG} = \frac{\frac{600}{\sqrt{3}}}{15} = 23.1\ \Omega\text{, and} \tag{3}$$

1040-V System: $$R_{NG} = \frac{\frac{1040}{\sqrt{3}}}{15} = 40.0\ \Omega. \tag{4}$$

For the 2400-V system, the proposed regulations require the maximum ground-fault current to be limited to 0.5 A. Thus, on the basis of Equation 1, the value of the grounding resistor is calculated as follows:

2400-V System: $$R_{NG} = \frac{\frac{2400}{\sqrt{3}}}{0.5} = 2.77\ \text{k}\Omega. \tag{5}$$

The distribution voltages of 480 V, 600 V, 1040 V, and 2400 V are used throughout this report instead of their associated motor voltages of 440 V, 550 V, 950 V, and 2300 V.

System Capacitance. With SHD cable, a braided, grounded copper/nylon shield encircles the insulation of each phase conductor. This physical arrangement results in line-to-ground capacitance distributed along the entire length of cable. The capacitance is essentially caused by parallel conductors (the phase conductor and the grounded shield) separated by a dielectric (the insulation around each conductor) for the length of the entire cable, as shown in Figure 6.

Although the shunt capacitance is distributed along the cable's length, it is lumped and connected from line to ground at the beginning of the cable for simplicity, as shown in Figure 4. As stated above, the capacitance is based on the physical properties of the cable, and the capacitance per unit length can be obtained from (Anaconda, 1977):

$$C_{pu} = \frac{7.354\xi}{\log_{10}\left(1 + \frac{2t}{d}\right)}\ \text{[pF/ft]} \tag{6}$$

where

C_{pu} = per-phase capacitance to ground per unit length [pF/ft]
ξ = 3.2 (Average value for EPR insulation)
t = insulation thickness
d = diameter under insulation.

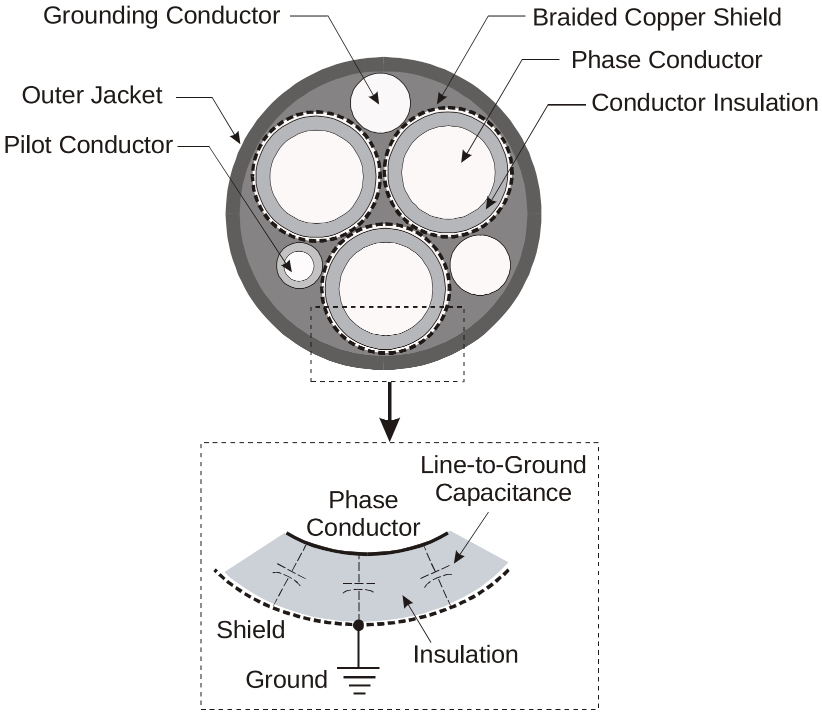

Figure 6. Cross-section of SHD cable illustrating shunt capacitance.

For the 5-kV rated cable shown in Figure 3, the per-phase capacitance per unit length is

$$C_{pu} = \frac{7.354(3.2)}{\log_{10}\left(1 + \frac{2(0.110)}{0.414}\right)} = 127 \text{ pF/ft.} \tag{7}$$

For the 2400-V system, a typical length of the continuous-miner cable is 800 ft, as specified by 30 CFR §18.35; therefore, the per-phase shunt capacitance is

$$C = (800 \text{ ft})\ (127 \text{ x } 10^{-12} \text{ F/ft}) = 0.102\ \mu\text{F.}$$

The per-phase shunt reactance for this capacitance at 60 Hz is calculated by

$$X_C = \frac{-1}{\omega C} = \frac{-1}{2\pi(60)(0.102x10^{-6})} = -26.0 \text{ k}\Omega, \tag{8}$$

and the total capacitive reactance, connected in parallel with the neutral grounding resistor in the single-phase diagram of Figure 5, is

$$\frac{X_C}{3} = \frac{-26{,}000}{3} = -8.67 \text{ k}\Omega. \tag{9}$$

Because of the low ohmic values for the neutral grounding resistors in the low and medium-voltage systems, the effects of system capacitance can be neglected in calculating ground-fault currents. The capacitance in Figure 5 can, therefore, be removed in performing quantitative analyses for low and medium-voltage systems, resulting in the simple circuit of Figure 7. However, for the 2400-V system, the value of capacitive reactance (Equation 9) is only 3.13 times the ohmic value of the neutral grounding resistor (Equation 5); therefore, system capacitance should be taken into account for accurate analyses.

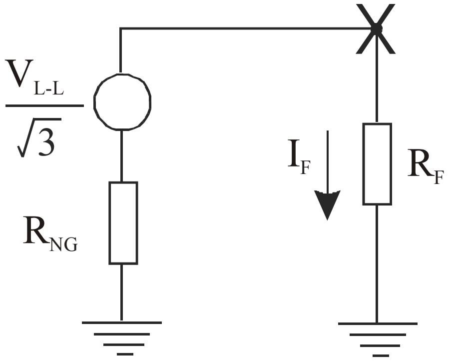

Figure 7. Simplified single-phase equivalent circuit of Figure 4 used for low and medium-voltage analyses.

Hazard Analysis. Three shock-hazard scenarios are presented to analyze the system response at each voltage level to determine the cable's safety effectiveness. The circuit models of Figures 5 and 7 will be used when appropriate.

***Scenario 1*.** *A metallic object, such as a nail or surveying spad, punctures a cable through its jackets and insulation into a phase conductor.*

Low voltage: The lack of shielding is the obvious safety deficiency associated with low-voltage cable. With *Scenario 1*, the metallic object will be elevated to line-to-ground potential (277 V or 346 V), which results in a serious shock hazard. This shock hazard can remain for an extended period since no action will be taken by the ground-fault relaying system, because the absence of shielding eliminates a ground path. If a person comes in contact with the metallic object, he/she will be subjected to this voltage, and the magnitude of the current through the body would essentially be limited by the victim's body resistance since the value of the neutral grounding resistor is relatively small compared with it. (The severity of this type of direct-contact shock is discussed in the "Shock Analysis" portion of this report.)

Medium voltage: The grounded shield, which encircles each phase of the cable, drastically reduces the possibility of this hazard. The shield provides a conductive path to ground, which causes the ground-fault relay at the power center to trip its associated circuit breaker and de-energize the cable when the ground-fault current exceeds the pickup setting (typically 6 A) of the relay.

The cable used for medium voltage has a braided copper/nylon shield. This shield provides a minimum copper coverage of 60%. Therefore, if the object has a small enough diameter, it may be able to penetrate through the open or nylon portion of the shield without contacting the copper portion. If this were to occur, a shock hazard would exist similar to the low-voltage case, except that the line-to-ground voltage (600 V) would be higher.

High voltage: With the high-voltage system, this shock hazard would essentially be eliminated. As with medium-voltage cable, high-voltage cable has a grounded nylon/copper shield with a minimum of 60% copper coverage. However, in addition to this shield, the insulation of each phase conductor is wrapped with semi-conducting tape. As a result, a conductive coverage of 100% essentially occurs. Therefore, any metallic object penetrating into a conductor would result in a ground fault that would trip the circuit breaker at the power center. Another important point is that the pickup setting (0.125 A) of the ground-fault relay is extremely sensitive compared with the setting (6 A) for medium voltage.

***Scenario 2*.** *The jackets and insulation of a cable are gouged to a point that water and dirt can penetrate to a power conductor.*

Low voltage: In a wet environment, water penetration can create a leakage-current path to the outer surface of the cable jacket. This hazard can go unnoticed for an indefinite period. With this situation, it is possible for a worker to receive a shock if he/she contacts a wet cable jacket within a few feet of the gouge. Again, the lack of shielding enhances the probability for this type of hazard. If the gouged area does not include a grounding conductor, a ground path does not exist for activating the ground-fault relaying system. Even if the gouged area does include a grounding conductor, the ground-fault current may not reach the 6-A threshold required for tripping because of the resistance of the conductive path from the phase conductor to the grounding conductor. Figure 7 can now be used to model this situation, with R_F representing the leakage-path resistance and I_F representing the leakage current. On the basis of Figure 7, the following calculations illustrate the maximum leakage-path resistance that would result in activating the ground-fault relay for the 480-V and 600-V systems:

$$R_{F_{\max}} = \frac{\frac{V_{L-L}}{\sqrt{3}}}{I_F} - R_{NG} \tag{10}$$

where, R_{Fmax} = Maximum resistance of the leakage path that will result in tripping the ground-fault relay [Ω],

$V_{L\text{-}L}$ = Line-to-line system voltage [V],

I_F = Pickup setting for the ground-fault relay [A], and

R_{NGR} = Resistance of the neutral grounding resistor [Ω].

For the 480-V system:

$$R_{F_{\max}} = \frac{\frac{V_{L-L}}{\sqrt{3}}}{I_F} - R_{NG} = \frac{\frac{480}{\sqrt{3}}}{6} - 18.5 = 27.7 \quad \Omega \tag{11}$$

For the 600-V system:

$$R_{F_{\max}} = \frac{\frac{V_{L-L}}{\sqrt{3}}}{I_F} - R_{NG} = \frac{\frac{600}{\sqrt{3}}}{6} - 23.1 = 34.6 \quad \Omega \tag{12}$$

Therefore, the ground-fault relays will not be activated for a leakage-path resistance greater than 27.7 Ω for a 480-V system and 34.6 Ω for a 600-V system.

Medium voltage: With the medium-voltage system, the gouged area does not need to include a grounding conductor because a braided nylon/copper shield encircles each individual phase and provides a ground path for ground-fault current to flow. However, because of the 6-A pickup setting of the ground-fault relay, the maximum resistance of the leakage path must still be extremely low for tripping to occur, as shown by the following equation:

$$R_{F_{\max}} = \frac{\frac{V_{L-L}}{\sqrt{3}}}{I_F} - R_{NG} = \frac{\frac{1040}{\sqrt{3}}}{6} - 40.0 = 65.5 \quad \Omega \tag{13}$$

High voltage: With the high-voltage system, the probability of this shock hazard is drastically reduced because of the very low pickup setting of 0.125 A required by the proposed regulations. Solving for the leakage resistance in this case is more complex since the cable capacitance must be taken into account. The ground-fault relay will not see the entire ground-fault current because most of the capacitive charging current returns to the transformer through the shunt capacitance. As a result, the ground-fault relay essentially sees the current in the neutral grounding resistor. Therefore, to produce a trip current greater than 0.125 A, the maximum resistance of the leakage path is limited to

$$R_{F_{\max}} \approx 8.0 \quad \text{k}\Omega. \tag{14}$$

This value shows that the enhanced sensitivity of the high-voltage system greatly reduces the potential shock hazard of *Scenario 2*. Even with a high-resistance leakage path up to 8.0 kΩ, the ground-fault relay will activate and de-energize the faulted cable.

Scenario 3. *A cable is damaged to the point that a bare energized conductor is exposed.*

Low voltage: To expose a bare power conductor the following layers of the low-voltage cable would have to be removed by means of ripping or tearing:

- A minimum of 205 mils of reinforced inner and outer jacketing,
- A minimum of 80 mils of insulation, and
- A layer of mylar tape.

If a worker comes in contact with the conductor, the line-to-neutral voltage would be imposed across the series combination of the body resistance (R_F in Figure 7) and the neutral grounding resistor (R_{NG} in Figure 7). As will be shown in the next section, the body resistance is significantly large compared with that of the neutral grounding resistor. Therefore, nearly the full line-to-neutral voltage (277 V or 346 V) will be impressed across the body. (The severity of this type of direct-contact shock is dependent upon the magnitude of the body current and is discussed in the "Shock Analysis" portion of this report.)

Medium voltage: For the medium-voltage cable, the following layers would have to be removed by means of ripping or tearing to expose a bare power conductor:

- A minimum of 205 mils of reinforced inner and outer jacketing,
- A braided nylon/copper shield,
- A layer of rubber-backed-fabric tape (lapped),
- A minimum of 80 mils of insulation, and
- A layer of mylar tape.

The thickness of the jackets and the insulation are the same as those of the low-voltage cable. However, two additional layers are provided by the shielding and the rubber backed fabric tape. If a worker comes in contact with the conductor, as with the low-voltage system, the line-to-neutral voltage would be imposed across the series combination of the body resistance (R_F in Figure 7) and the neutral grounding resistor (R_{NG} in Figure 7). As will be shown in the next section, the body resistance is significantly large compared with that of the neutral grounding resistor. Therefore, nearly the full line-to-neutral voltage (600 V) will be impressed across the body. (The severity of this type of direct-contact shock is dependent upon the magnitude of the body current and is discussed in the "Shock Analysis" portion of this report.)

High voltage: Exposing a bare power conductor in the high-voltage cable would require the following layers to be removed by means of ripping or tearing:

- A minimum of 220 mils of reinforced inner and outer jacketing,
- A braided nylon/copper shield,
- A layer of semi-conducting tape (lapped),
- A minimum of 110 mils of insulation, and
- 15 mils of extruded semi-conducting compound.

The combined thickness of the inner and outer jackets is increased by 7.3%, and the insulation thickness is increased by 37.5% compared with the low and medium-voltage cables. The rubber-backed-fabric tape is replaced by a layer of semi-conducting tape, and the mylar tape is replaced with 15 mils of extruded semi-conducting compound. It should be noted that the separate colors required for the inner (green) and outer jackets (orange) increase the possibility for visually detecting damaged jackets on the cable. Since system capacitance is not negligible at this voltage, Figure 5 is used to describe the direct-contact shock, instead of Figure 7. If a worker comes in contact with the conductor, the line-to-neutral voltage would be imposed across the series combination of the body resistance (R_F) and the parallel combination of the neutral grounding resistor (R_{NG}) and the reactance due to system capacitance ($X_C/3$). The total equivalent impedance is given by $R_F + R_{NG} \parallel -jX_C/3$). As will be shown in the next section, body resistance can be comparable to the impedance of $R_{NG} \parallel -jX_C/3$ ($2639\underline{/-17.72^\circ}$). Therefore, the voltage across the body is a function of body resistance. (The severity of this type of direct-contact shock is dependent upon the magnitude of the body current and is discussed in the "Shock Analysis" portion of this report.)

SHOCK ANALYSIS

A voltage source is usually the cause of electric shock. However, shock is solely quantified in terms of current. To better understand why current is used to define the severity of electric shock, consider a voltage source applied across a person's extremities. With a voltage source, the amount of current through the victim's body depends upon body resistance; and Ohm's Law ($I = V/R$) dictates the magnitude of current. Therefore, body current can vary dramatically for a given voltage, depending on the physical conditions that affect body resistance at the time of the shock.

The circuits of Figures 5 and 7 are used to determine body current (I_F) for a given body resistance (R_F) at the different voltage levels. Also, the difference between the ground-fault protection schemes for high voltage and medium/low voltage are discussed. Body currents are then calculated and compared for the various voltage levels.

Body Resistance. Total body resistance includes the contact resistances between electrical conductors and the skin at points of entrance and exit of current, the resistance of the skin, and the internal resistance of the body (Keesey and Letcher, 1970). Skin resistance is the dominant factor since its value is much greater than the combined value of internal body tissues. But skin resistance changes with regard to current density, temperature, sweat-gland secretion, and state of excitement (Jacimovic, 1982). Thus, it is impossible to consider body resistance as a constant value. Research indicates that body resistance can vary from 10 kΩ down to 1 kΩ under various conditions, and may even be as low as 200 Ω if skin resistance is lowered by the presence of a cut. Predicting the physiological response to a given voltage necessitates an assumption for the value of body resistance. Electrical safety standards have been developed in the United States by the Institute of Electrical and Electronic Engineers (IEEE) and in Europe by the International Electrotechnical Commission (IEC). Body resistances used by these two professional organizations to evaluate electrical safety hazards are presented in Figure 8. As shown in the figure, the IEEE uses a1000-Ω value of body resistance for all situations, whereas the IEC value is a function of the contact voltage, but essentially approaches 650 Ω for all contact voltages above 600 V. An even more conservative value of 500 Ω is used by Underwriters' Laboratory (UL) for defining the operating characteristics of single-phase 120-V ground-fault current interrupters (GFCIs). For this report, body currents will be calculated over a range of representative body resistances, based on the values used by the above mentioned organizations.

Body Currents. Using the circuit models in Figures 5 and 7, body currents are calculated over a body-resistance range of 400 Ω to 2000 Ω. The results of the analysis are shown in Figure 9. Interestingly, the body currents caused by direct-contact shocks for the 2400-V system are less than those caused by the two low-voltage systems (480 V and 600 V) up to a body resistance of approximately 650 Ω, and less than those of the medium-voltage system (1040 V) up to a body resistance of approximately 2000 Ω. This phenomenon occurs because a 0.5-A ground-fault current limit is required for the 2400-V system, whereas a 15-A current limit is used for the low and medium-voltage systems.

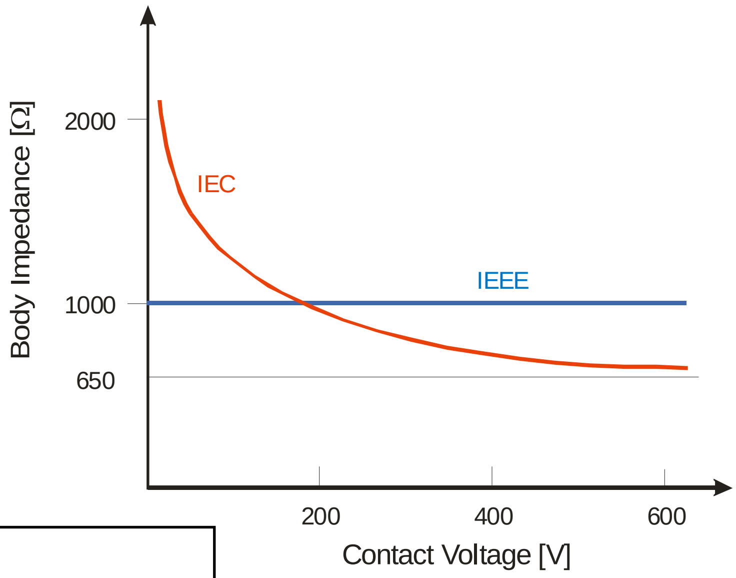

Figure 8. Body impedances used by the IEEE and IEC for evaluating electrical safety.

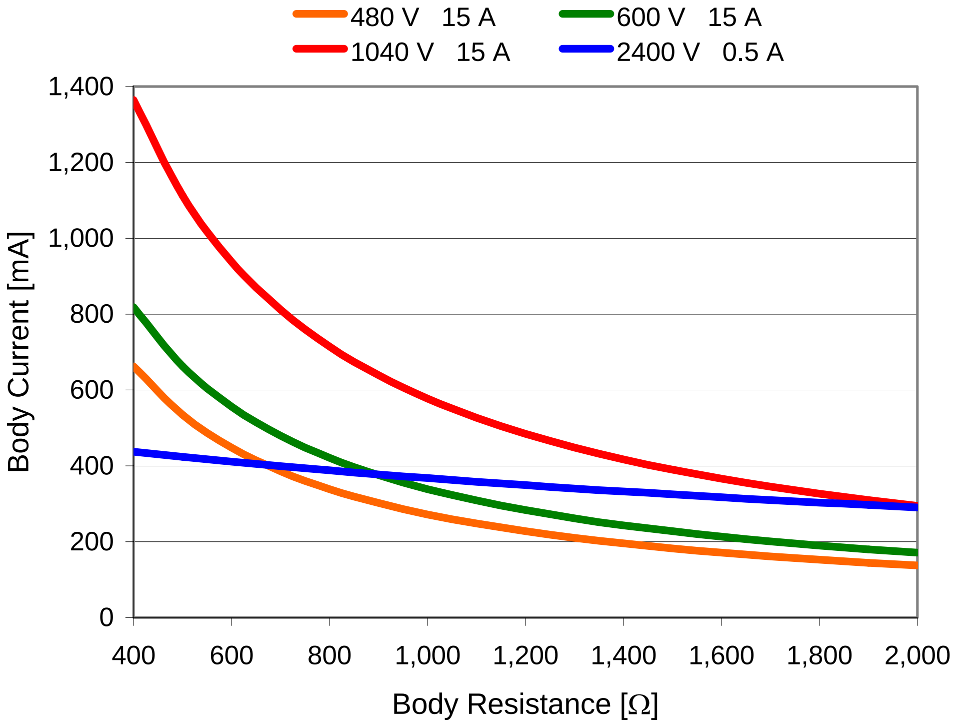

Figure 9. Body currents over a range of body resistances for the various system voltages.

Ground-Fault Protection. Zero-sequence relaying, also referred to as balanced flux relaying, is the primary method of ground-fault protection used at all voltage levels, although the relays used for high voltage are more sensitive and sophisticated. As shown in Figure 10, the circuitry consists of a single window-type current transformer (CT) and a ground-fault relay. The three line conductors pass through the CT core, forming the primary winding. Therefore, the primary current is the phasor sum of the three line currents. Under normal operating conditions, the continuous-miner currents flow and return through the CT, resulting in a balanced condition, and the three line currents sum to zero. However, if a ground fault occurs, the ground-fault current will return through the grounding conductor, outside of the CT core. This results in an unbalanced situation and the line currents no longer sum to zero. Instead, a resultant current is induced in the CT secondary which activates the ground-fault relay to trip the circuit breaker if the pickup setting of the relay is exceeded.

With low and medium-voltage systems, federal regulations require the ground-fault protection to be instantaneous (no intentional time delay), with the ground-fault-relay pickup set at less than or equal to 40% of the maximum ground-fault current (6 A for a 15-A current limit). The ground-fault protection for the 2400-V system is much more sensitive. The proposed regulations specify a pickup setting of 0.125 A, which is 98% less than that of the low and medium-voltage systems. Because of high motor-starting currents, which can induce currents in the grounding conductors greater than 0.125 A, the proposed regulations allow a time delay of 0.05 s to prevent nuisance tripping. The proposed regulations also require each 2400-V circuit to have a *look-ahead* circuit that measures the cable impedance when the circuit is off-line. If the look-ahead circuit detects a ground-fault, the relay prevents the circuit breaker from being closed.

Potential relaying is also required by the proposed regulations for backup ground-fault protection. Figure 10 shows the primary winding of a potential transformer (PT) connected across the neutral grounding resistor, while the secondary winding is connected across a voltage-sensing ground-fault relay. A maximum 0.25-s delay is permitted to allow coordination with primary ground-fault protection. If current flows through the grounding conductor, a voltage is developed across the grounding resistor. When the voltage rises above a preset level, the ground-fault relay causes the circuit breaker to trip after the specified time delay.

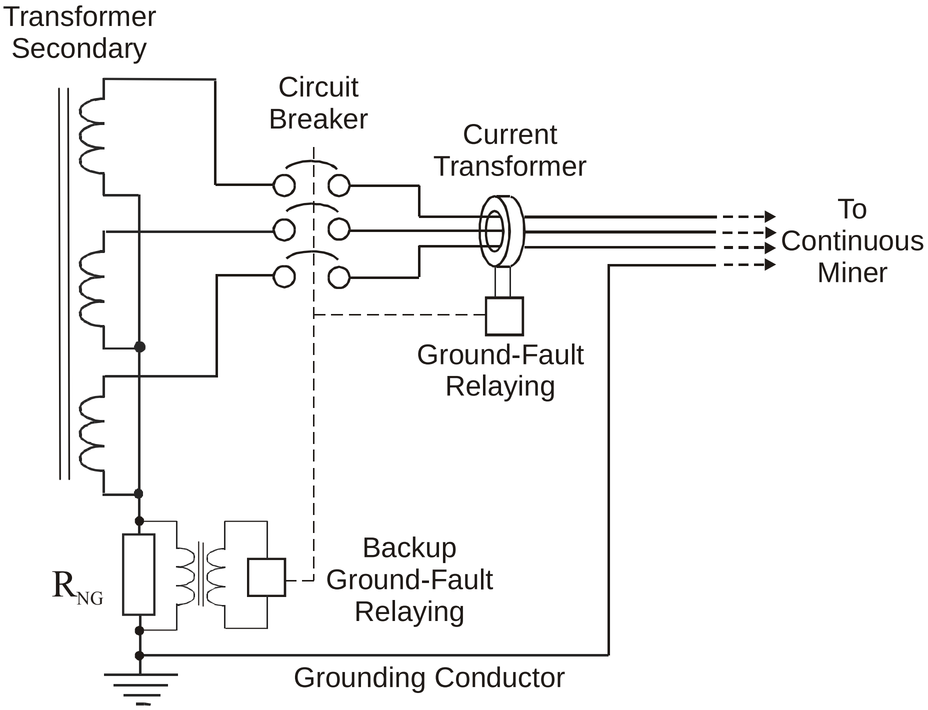

Figure 10. Ground-fault relaying.

Ventricular Fibrillation. Ventricular fibrillation is considered the most dangerous electric shock hazard since only a small amount of current is required to disrupt the natural rhythm of the heart. Therefore, its threshold will be utilized for comparing shock severity for the various voltage levels. For ventricular fibrillation to occur, the shock current needs to pass through the heart during the phase when the ventricles are starting to relax after a contraction (Lee, 1966). When fibrillation occurs, the effective pumping action of the heart ceases, the pulse disappears, and death usually occurs within minutes. The threshold of ventricular fibrillation is not adequately known nor easily determined since experimentation on humans is not realistic; however, approximations have been developed based on animal experiments. The statistical data obtained from these experiments have been weight scaled and fitted to equations for predicting minimum threshold values of fibrillation.

The most widely accepted prediction was developed by Charles Dalziel (1969). According to Daziel, the three major factors of concern for ventricular fibrillation are body weight, current magnitude, and shock duration. He used the results of animal studies, conducted by Ferris (1936) and Kouwenhoven (1959), to establish an equation for the minimum threshold of fibrillation. Dalziel developed the following equation for predicting the minimum threshold of fibrillation for a body weight of 50 kg (110 lb):

$$I = \left[\frac{116}{\sqrt{t}} \right] \quad (8.3\,ms \le t \le 5.0\,s) \tag{15}$$

where

I = minimum current (mA, 60 Hz) at which fibrillation occurs for a pathway through major extremities and

t = duration (s) of the shock.

The equation states that fibrillation current is inversely proportional to the square root of exposure time and is represented graphically in Figure 11. According to Dalziel, the area to the left of the line is considered the *safe* area with respect to ventricular fibrillation. The equation is based on the 0.5 percentile. In other words, ventricular fibrillation should only occur in one out of every 200 people if the fibrillation predictions of the equation are attained.

It should be emphasized that Dalziel's ventricular-fibrillation prediction is only used here as a frame of reference for illustrating the severity for a direct-contact shock at the various voltage levels and that none of the protective relaying systems, regardless of voltage, are designed to protect against ventricular fibrillation. Since the prediction is based on research studies conducted on animals, it should not be accepted as a definitive means for determining whether or not a current is lethal.

Relaying Characteristics. To give an indication of the difference in relay sensitivities between the 2400-V system and the medium and low-voltage systems, the ground-fault clearing characteristics are shown along with Dalziel's ventricular fibrillation prediction in Figure 12. The ground-fault relays for all voltages are definite-time types. The operating time for this type of relay is independent of the actuating quantity and is relatively constant for any current which exceeds its pickup setting. The maximum pickup settings for the low and medium-voltage relay is 6 A, whereas only 0.125 A is required for the 2400-V system. The total clearing time is the sum of the operating times of the ground-fault relay, the undervoltage release (or shunt trip), and the breaker. Once contact separation is initiated, a molded-case breaker, used for low and medium voltages, will typically clear in one or two cycles, while a vacuum breaker, used for high voltage, will typically clear at the first current zero. Therefore, a conservative value for the operating time for both types of breakers is 2 cycles or 0.033 s. If operating times of 0.05 s are assumed for the undervoltage release and for the ground-fault relay, the total clearing time would be 0.133 s. An additional 0.050 s must be added to the clearing time of the 2400-V system to take into account the time delay permitted by the proposed regulations. The total clearing characteristics are shown in Figure 12. It is obvious that neither system is designed to protect against ventricular fibrillation; however, the enhanced sensitivity of the 2400-V system is evident. In fact, the low and medium-voltage pickup setting is 48 times higher than that of the 2400-V system.

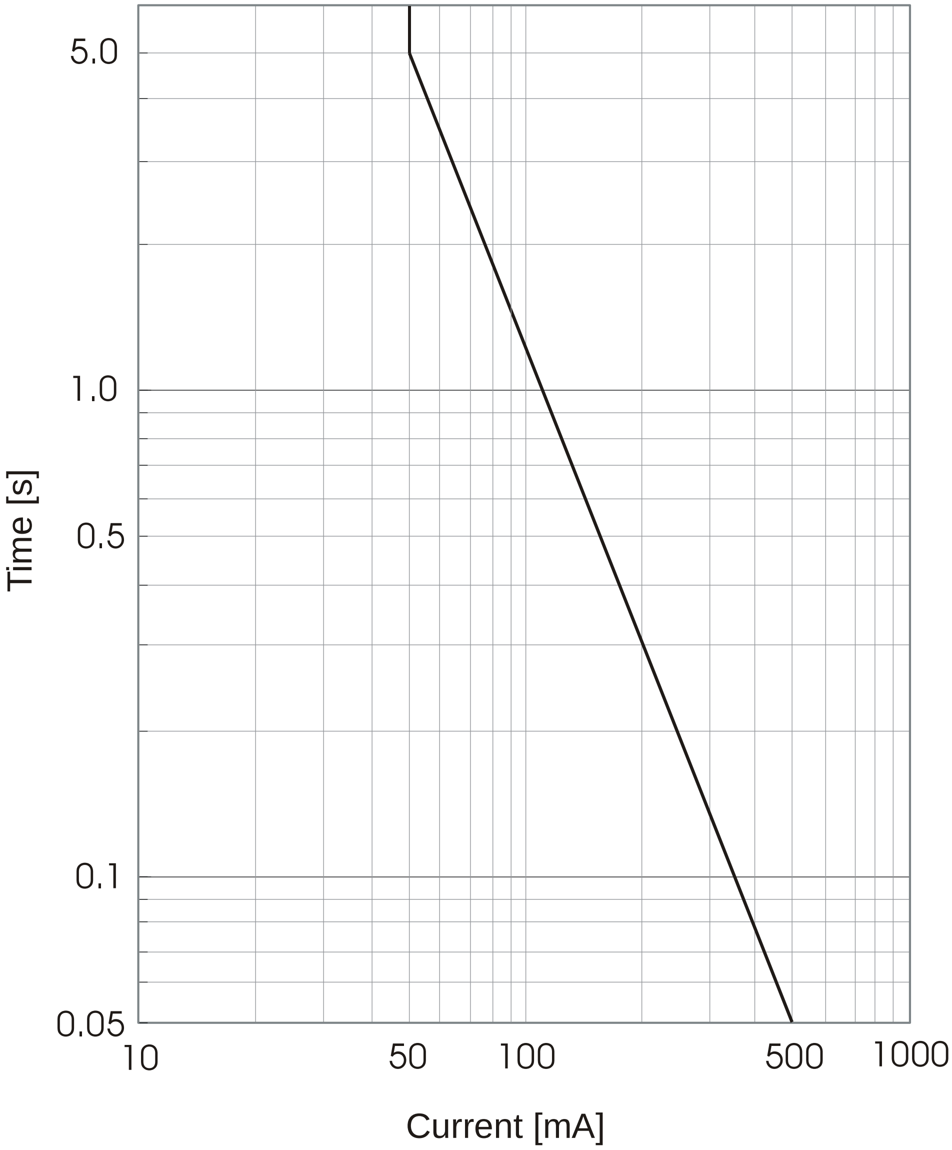

Figure 11. Charles Dalziel's prediction for ventricular fibrillation.

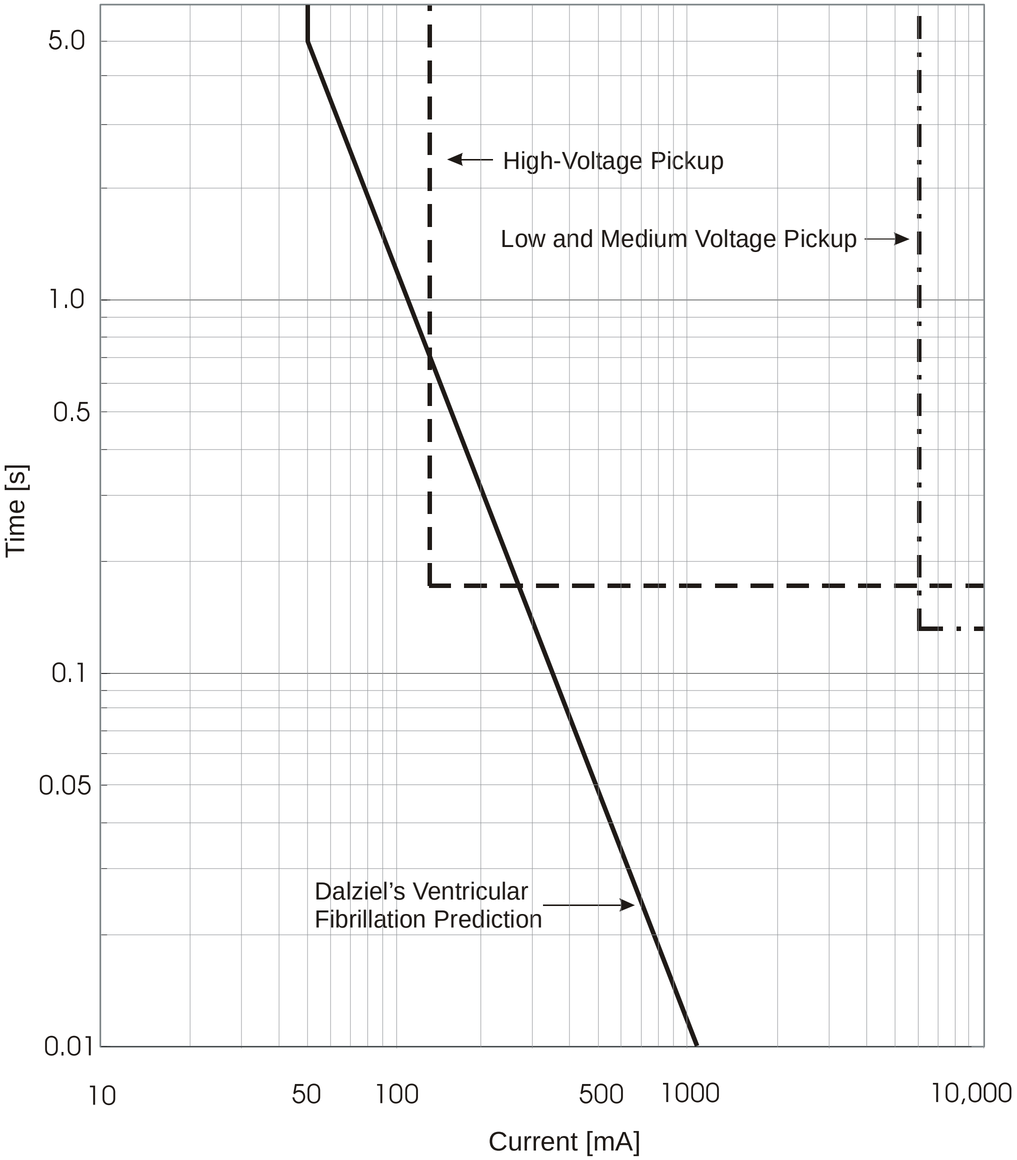

Figure 12. Time-current clearing characteristics for the different voltage levels.

Body-Current Analysis. Body currents for body resistances of 500 Ω, 650 Ω, and 1000 Ω are plotted along with Dalziel's ventricular-fibrillation prediction and the ground-fault-relay clearing characteristics in Figures 13, 14, and 15, respectively. These values are used to coincide with the values used by the IEEE, IEC, and UL.

500-Ω Body Resistance. As shown in Figure 13, it is interesting to note that the body current for a direct-contact shock on a 2400-V system is less than those of the 480-V, 600-V, and 1040-V systems. Because of the sensitive pickup (0.125 A) of the ground-fault relay for the 2400-V system and the low body resistance, the trailing cable would be de-energized at the circuit's clearing time. In contrast, the ground-fault relays for the 480-V, 600-V, and 1040-V systems will not activate because the pickup setting of 6 A is significantly greater than the body current associated with each voltage level. Thus, it is obvious that the 2400-V system is safer than the low and medium-voltage systems for a direct-contact shock with a 500-Ω body resistance.

650-Ω Body Resistance. Body currents for the various voltage levels are shown in Figure 14 for a body resistance of 560 Ω. At this slightly higher value of body resistance, the body current for the high-voltage (2400 V) system is still lower than those of the 480-V, 600-V, and 1040-V systems. Similar to the 500-Ω case, the ground-fault relay for the 2400-V system would trip, while the ground-fault relays for the 480-V, 600-V, and 1040-V systems would not. Again, the 2400-V system is safer than the low and medium-voltage systems for a direct-contact shock with a 650-Ω body resistance.

1000-Ω Body Resistance. Figure 15 shows the body currents at the various voltages for a body resistance of 1000 Ω. Although the body currents are lower at low voltage (480 V and 600 V), the body current for the medium-voltage (1040 V) system is still greater than that of the 2400-V system. The ground-fault relay would trip, de-energizing the 2400-V system at the circuit's clearing time. Again, the ground-fault relays for the 480-V, 600-V, and 1040-V systems will not activate because their associated pickup settings are greater than the body currents. Therefore, the 2400-V system also demonstrates enhanced safety at this value of body resistance, compared with the medium and low-voltage systems. The results of the body-current analysis are summarized in Table I.

TABLE I. SUMMARY OF BODY CURRENT ANALYSIS

Voltage	Body Resistance = 500 Ω		Body Resistance = 650 Ω		Body Resistance = 1000 Ω	
	Body Current [mA]	GFR Tripped	Body Current [mA]	GFR Tripped	Body Current [mA]	GFR Tripped
480 V	534	NO	415	NO	272	NO
600 V	662	NO	515	NO	339	NO
1040 V	1,112	NO	870	NO	577	NO
2400 V	424	YES	405	YES	368	YES

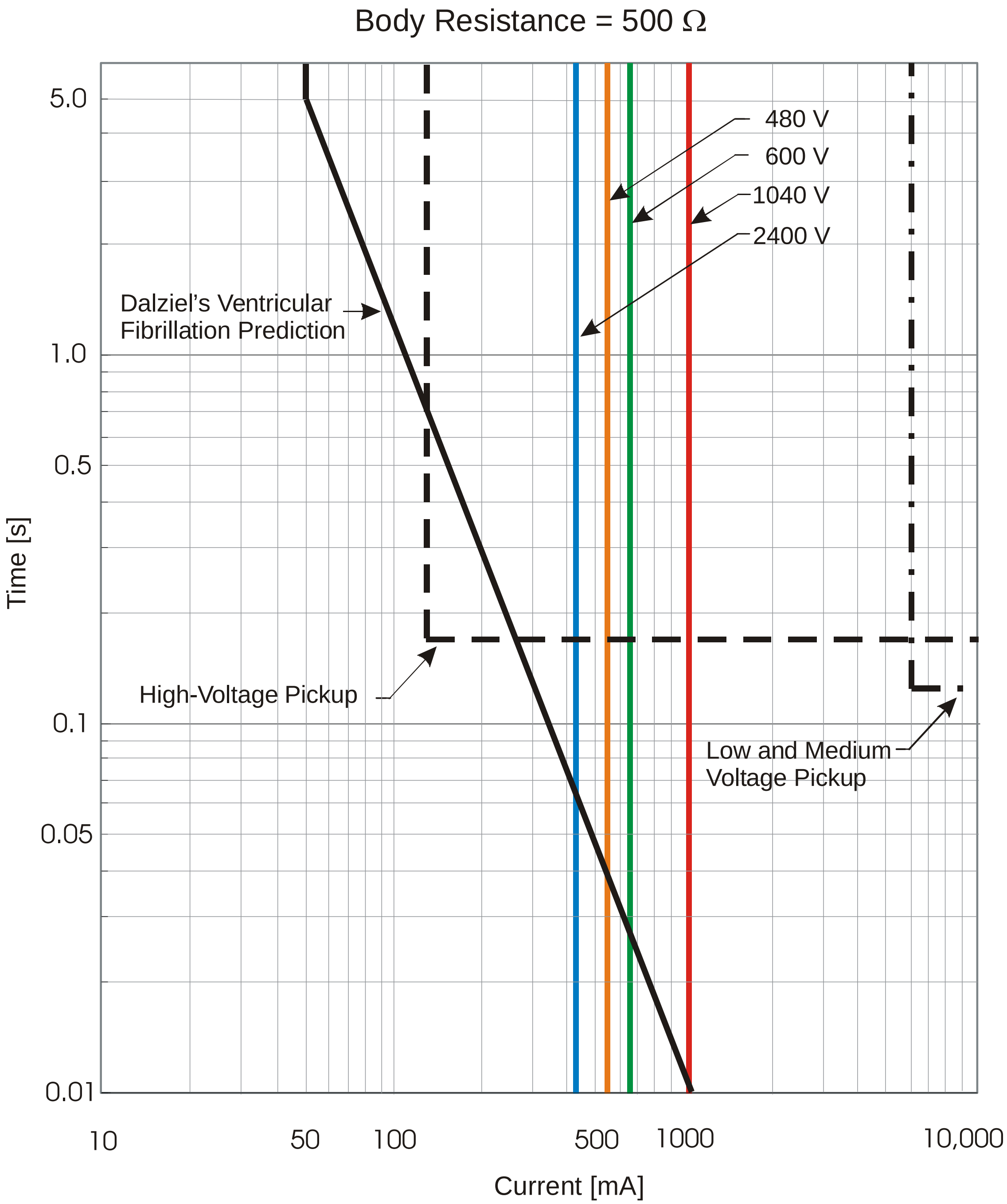

Figure 13. Body currents for a body resistance of 500 Ω at the various voltages.

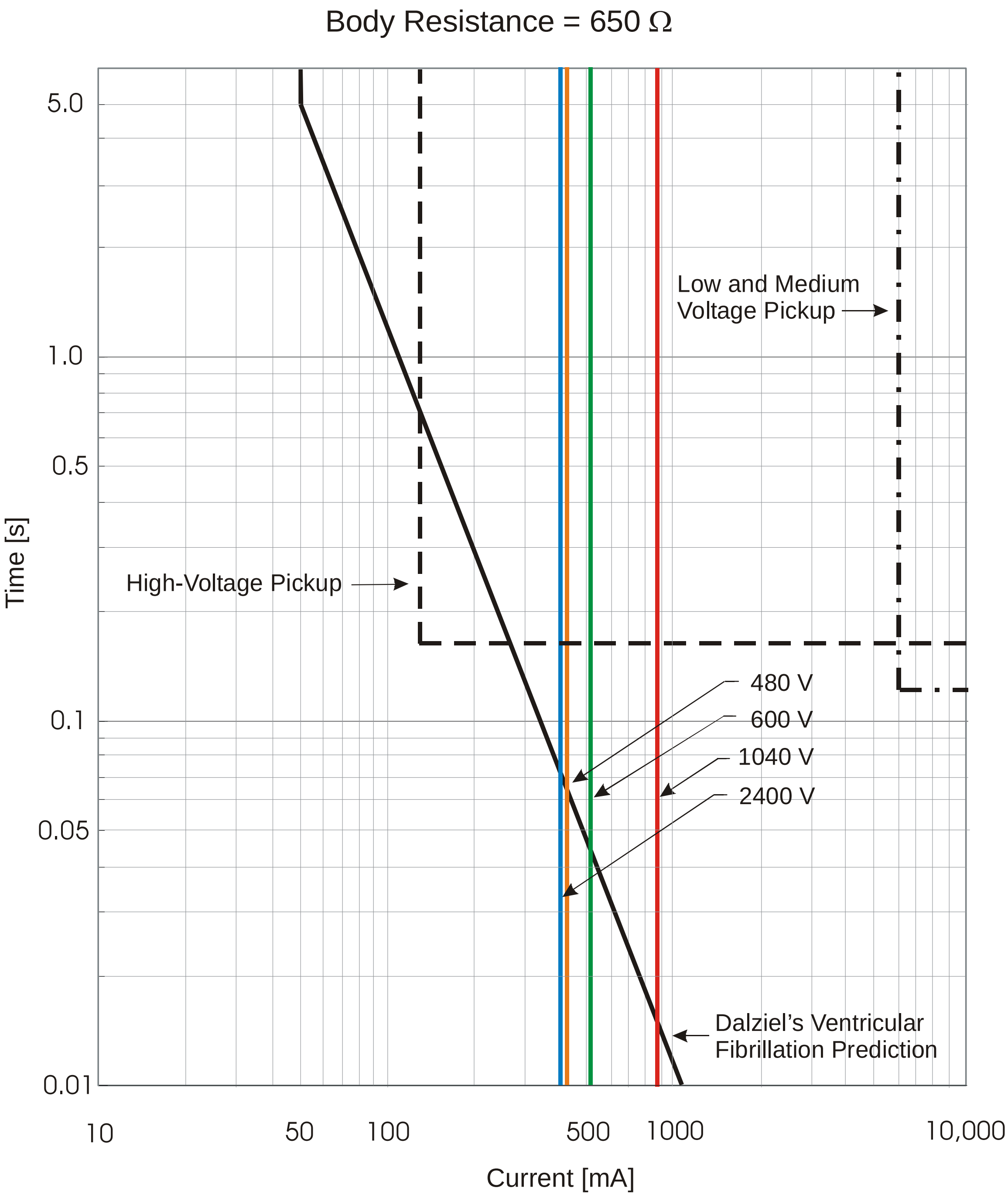

Figure 14. Body currents for a body resistance of 650 Ω at the various voltages.

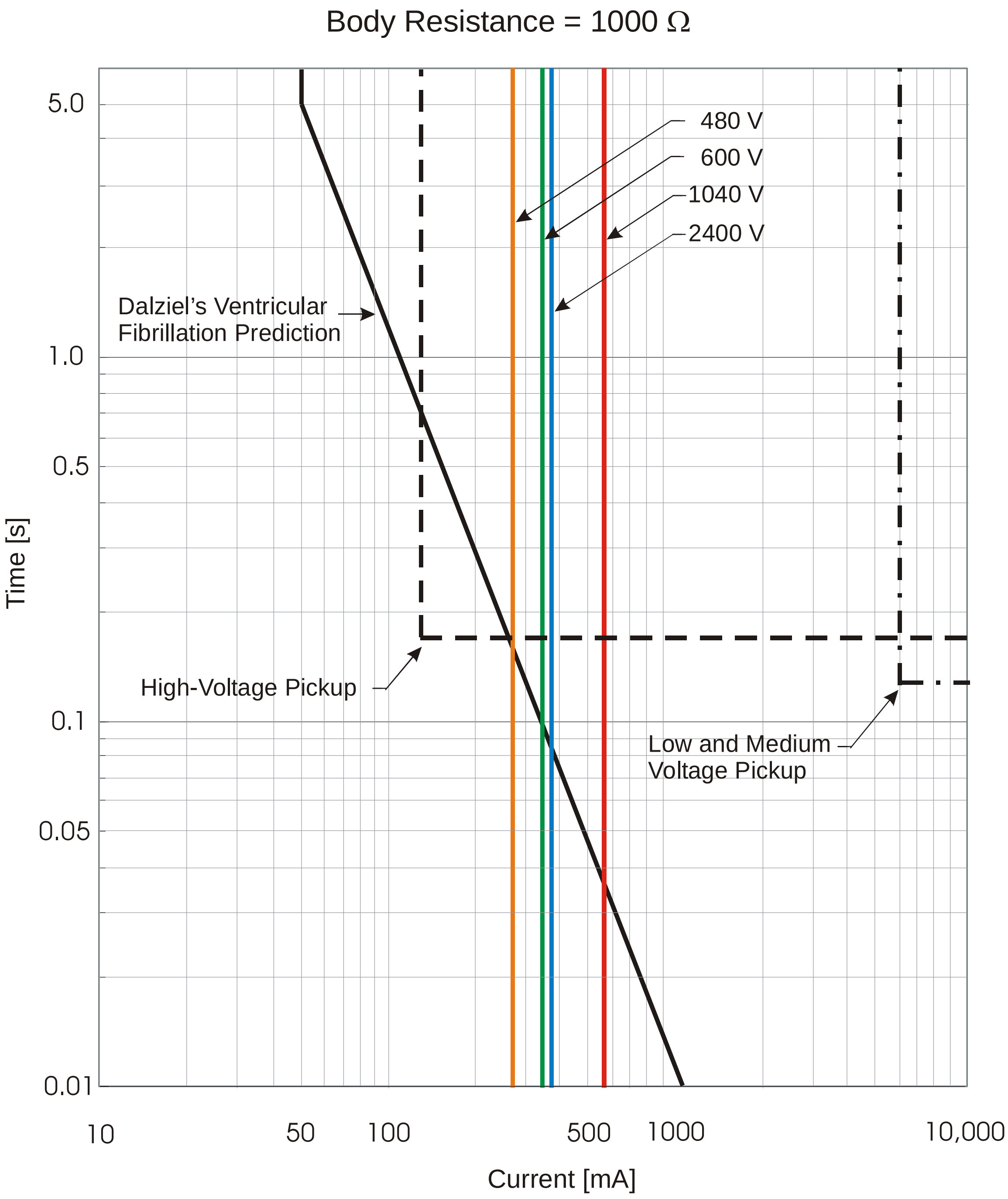

Figure 15. Body currents for a body resistance of 1000 Ω at the various voltages.

CONCLUSIONS

An electrical safety analysis was performed for continuous-miner trailing cables operating at low (480 V and 600 V), medium (1040 V), and high voltages (2400 V). The intent of the analysis was to determine if an increased shock hazard occurs with the 2400-V system, as compared with existing low and medium-voltage systems. To approach this issue, the analysis was directed to answer the following two questions:

1. Is a trailing cable on a 2400-V system more likely to be damaged and cause a shock hazard as compared with cables used on existing low and medium-voltage systems?

   and

2. If a direct-contact shock hazard does occur on a 2400-V system, is it more dangerous than one from an existing low or medium-voltage system?

Question 1 was addressed by analyzing the cable construction at the various voltage levels. Three representative shock-hazard scenarios were selected to evaluate the effectiveness of each cable type:

Scenario 1. *A metallic object, such as a nail or surveying spad, punctures a cable through its jackets and insulation into a phase conductor.*

Scenario 2. *The jackets and insulation of a cable are gouged to a point that water and dirt can penetrate to a power conductor.*

Scenario 3. *A cable is damaged to the point that a bare energized conductor is exposed.*

The analysis of *Scenario 1* reveals that the cable construction used for 2400-V would provided the highest degree of protection. The lack of a conductive, grounded shield on low-voltage cables results in the absence of a ground path, which prohibits the activation of the ground-fault relay. The metallic object is then elevated to the line-to-ground voltage, which can remain unnoticed and present a serious shock hazard for an indefinite period. The grounded shield of the medium voltage cable significantly reduces this hazard by providing a return path for ground-fault current so that the ground-fault relay trips when its pickup setting of 6 A is exceeded. However, the medium-voltage cable utilizes a braided copper/nylon shield, which provides a minimum copper coverage of 60%. Therefore, if the metallic object has a small enough diameter, it may be able to penetrate through the open or nylon portion of the shield without contacting the copper portion. If this were to occur, a shock hazard would exist similar to the low-voltage case, except that the line-to-ground voltage would be higher. With the 2400-V cable, this shock hazard would essentially be eliminated. In addition to the nylon/copper shield, the insulation of each phase conductor is wrapped with semi-conducting tape. As a result, a conductive coverage of 100% effectively occurs. Therefore, any metallic object penetrating into a power conductor would result in a ground fault that would trip the circuit breaker at the power center.

The analysis of *Scenario 2* also shows that the cable construction used for 2400-V systems provides the highest degree of protection. In a wet environment, water penetration can create a leakage-current path to the outer surface of the cable jacket. With low-voltage cable, this hazard can go unnoticed for an indefinite period, and it is possible for a worker to receive a shock if he/she contacts the wet cable jacket within a few feet of the gouge. With the medium-voltage system, the braided nylon/copper shield encircles each individual phase and provides a ground path for ground-fault current to flow. However, because of the 6-A pickup setting of the ground-fault relay, the resistance of the leakage path must be extremely low (65.5 Ω) for tripping to occur. With the 2400-V system, the probability of this shock hazard is drastically reduced because of the very low pickup setting of 0.125 A required by the proposed regulations. Even with a high-resistance leakage path of 8.0 kΩ, the ground-fault relay will activate and de-energize the faulted cable.

The analysis of *Scenario 3* shows that the cable construction used for 2400-V systems decreases the likelihood of exposing a bare power conductor by means of ripping or tearing. The combined thickness of the inner and outer jackets of the high-voltage cable is increased by 7.3% compared with the low and medium-voltage cables, while the insulation thickness is increased by 37.5%. In addition, high-voltage cables employ 15 mils of extruded semi-conducting compound around each power conductor adding another layer of protection. It should also be noted that the separate colors required for the inner (green) and outer jackets (orange) of the high-voltage cable increase the possibility for visually detecting damaged jackets on the cable before accidental contact occurs.

Question 2 was addressed by analyzing the severity of direct-contact shocks at the different voltage levels and at various body resistances. Circuit models were developed to calculate body currents over a body-resistance range of 400 Ω to 2 kΩ. The results of the analysis show that body currents caused by direct-contact shocks for the 2400-V system are less than those caused by the low-voltage systems (480 V and 600 V) up to a body resistance of approximately 600 Ω, and less than those of the medium-voltage system (1040 V) up to a body resistance of approximately 2 kΩ. This phenomenon occurs because a 0.5-A ground-fault current limit is required for the 2400-V system, whereas a 15-A current limit is used for the low and medium-voltage systems.

Ground-fault clearing characteristics and Dalziel’s ventricular fibrillation prediction were then plotted, along with the body currents for body resistances of 500 Ω, 650 Ω, and 1000 Ω to correspond with values used by UL, IEC, and IEEE, respectively. With a 500-Ω body resistance, the body current for a direct-contact shock on a 2400-V system is less than those of the 480-V, 600-V, and 1040-V systems, and the body current for the 2400-V is greater than the 0.125-A pickup setting of the ground-fault relay, which results in de-energizing the trailing cable. In contrast, the ground-fault relays for the 480-V, 600-V, and 1040-V systems will not activate because the pickup setting of 6 A is significantly greater than the body current associated with each voltage level. Thus, it is obvious that the 2400-V system is safer than the low and medium-voltage systems for a direct-contact shock with a 500-Ω body resistance.

At the slightly higher value of 650 Ω for body resistance, the body current for the high-voltage (2400 V) system is still lower than those of the 480-V, 600-V, and 1040-V systems. Similar to the 500-Ω case, the ground-fault relay for the 2400-V system would trip, while the ground-fault relays for the 480-V, 600-V, and 1040-V systems would not. Again, the 2400-V system is safer than the low and medium-voltage systems for a direct-contact shock with a 650-Ω body resistance.

Although the body currents are lower at low voltage (480 V and 600 V) for a body resistance of 1000 Ω, the body current for the medium-voltage (1040 V) system is still greater than that of the 2400-V system. Again, the ground-fault relay would trip, de-energizing the 2400-V system, while the ground-fault relays for the 480-V, 600-V, and 1040-V systems will not activate because their pickup setting is greater than the predicted body currents. Therefore, the 2400-V system demonstrates enhanced safety at a 1000-Ω body resistance, compared with the medium and low-voltage systems.

In summary, the results of the analyses performed in this report strongly indicate that the cable used for 2400-V continuous miners provides a greater level of protection against electric shock as compared with the cables used at low and medium voltages. This level of protection is the result of enhanced cable construction in conjunction with a very-low ground-fault-current limit of 0.5 A and a very-low ground-fault pickup setting of 0.125 A. Therefore, on the basis of this analysis, handling cable used on a 2400-V continuous miner in the same fashion as on low and medium-voltage continuous miners would not present an increased shock hazard.

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ACKNOWLEDGEMENT

Specification sheets for trailing cables and cable samples were obtained from Mark Fuller of AmerCable, Inc.